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REPORT
ON
A STUDY ON THE BIOGASIFICATION OF PEAT

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TABLE OF CONTENTS

		Page
1.	Resumé, Conclusions et Recommendations	iii
1.	SUMMARY, CONCLUSIONS AND RECOMMENDATIONS	1
	1.1 Summary	1
	1.2 Conclusions	1
	1.3 Recommendations	2
2.	INTRODUCTION	4
3.	OBJECTIVES AND SCOPE	7
	3.1 Objectives	7
	3.2 Scope of the Study	7
4.	BIOGASIFICATION OF PEAT	9
	4.1 Review of Literature	9
	4.1.1 General	9
	4.1.2 A Review of Early Work	9
	4.1.3 A Review of Recent Work	10
	4.1.3.1 Work Done at IGT	10
	4.1.3.2 Work Done at Dynatech R/D	11
	4.2 Description of the Processes	12
	4.2.1 General	12
	4.2.2 Biogasification Using Alkaline-Oxidative Pretreatment	13
	4.2.2.1 Harvesting/Slurry Preparation	13
	4.2.2.2 Pretreatment Reactor (Alkaline Oxidation)	13
	4.2.2.3 Liquid Solids Separator	15
	4.2.2.4 Fermentation Reactor	15
	4.2.2.5 Gas Purification Unit	15
	4.2.3 Biothermgas Process	16
	4.3 Discussion of Current U.S. Research	18
	4.4 Process Plant Economics	24
	4.4.1 General	24
	4.4.2 Dynatech Process	26
	4.4.3 Biothermgas Process	33

TABLE OF CONTENTS (continued)

		Page
4.5	Economic Comparison With Other Peat Processes	38
4.6	Environmental and Other Considerations	48
5.0	RECOMMENDATIONS FOR FUTURE WORK	51
	List of Figures	54
	List of Tables	55
	Nomenclature	56
	APPENDIX A - ANNOTATED BIBLIOGRAPHY	57

1. RESUME, CONCLUSIONS ET RECOMMANDATIONS

1.1 Résumé

La société ADI Limited a été autorisée à effectuer une étude sur la biogazéification de la tourbe, par le ministère des Approvisionnements et Services du gouvernement du Canada au début de 1982, à la suite d'une proposition spontanée soumise par ADI au coordinateur, Energie renouvelable, Conseil national de recherches du Canada.

Le présent rapport examine la littérature sur la biogazéification de la tourbe, étudie la recherche actuelle aux Etats-Unis, décrit les deux procédés prometteurs de biogazéification, fait une analyse économique de ces deux procédés et fait aussi une comparaison économique avec d'autres emplois de la tourbe. Les conclusions découlant de cette étude et les recommandations en vue d'un plan d'action éventuel lié à la biogazéification se trouvent dans ce rapport. En annexe on présente une bibliographie annotée sur le sujet.

1.2 Conclusions

On est arrivé aux conclusions suivantes après une étude et une évaluation des procédés actuellement en cours de développement pour la biogazéification de la tourbe.

1. La tourbe est un mélange de substances complexes telles que la lignine, la cellulose, l'hémicellulose, etc., qui présentent toutes des degrés différents, mais restant relativement faibles, de biodégradabilité. Les concen-

trations relatives de ces substances complexes peuvent varier d'une tourbière à l'autre.

2. La biogazéification de la tourbe est techniquement faisable si l'on en juge par les études expérimentales faites jusqu'à présent; le pré-traitement de la tourbe brute (de différentes façons) peut améliorer la biodégradabilité de façon marquée.

3. Les deux procédés prometteurs sont (i) la biogazéification utilisant un pré-traitement alcalin-oxydant créé par Dynatech R/D et (ii) BIOTHERMGAS créé par l'Institute of Gas Technology (IGT) aux Etats-Unis.

4. Les deux procédés sont aux premiers stades de développement, c'est-à-dire dans la phase de laboratoire et n'ont pas encore atteint la phase de démonstration. Ces deux procédés exigent encore du travail de développement. BIOTHERMGAS a été étudié seulement avec d'autres biomasses, mais on pense qu'on peut l'appliquer à la tourbe extraite par voie humide, moyennant des études supplémentaires d'adaptation.

5. Une analyse économique préliminaire de ces deux procédés de biogazéification et une comparaison avec d'autres emplois de la tourbe ont montré que le coût d'unité d'énergie le plus bas (compte non tenu de la tourbe utilisée dans le procédé) a été obtenu dans le procédé de carbonisation par voie humide, suivi du procédé BIOTHERMGAS et du procédé Wetox, alors que le coût énergétique le plus élevé a été obtenu avec le procédé Dynatech. Compte tenu néanmoins, des coûts d'exploitation et d'entretien réalistes et des facteurs d'échelle, le procédé BIOTHERMGAS devenait moins intéressant économiquement (avec un coût d'unité d'énergie faible). Cette analyse laisse penser que la production de tourbe comprimée reste aussi intéressante du point de vue économique lorsque elle est faite à grande échelle. On doit cependant tenir compte du fait que ce procédé exige une tourbe de qualité combustible à 50 % MC, qui présente un coût plus élevé que l'hydro-tourbe utilisé dans les autres procédés.

6. D'après des discussions avec l'Ontario Research Foundation, nous avons appris que le procédé Wetox est prêt pour la démonstration, avec une capacité de 115 t/d, pour produire de l'eau chaude et de la vapeur. Le procédé de carbonisation par voie humide semble prêt pour une application commerciale, selon les détenteurs américains de la licence.

7. On prévoit que les répercussions environnementales de l'effluent du procédé BIOTHERMGAS seraient minimales par rapport aux répercussions néfastes possibles de l'effluent solubilisé du procédé Dynatech.

8. Les procédés Wetox et de carbonisation par voie humide produisent des eaux usées très concentrées qu'on devrait traiter avant l'élimination. Des études au laboratoire ont montré que ces eaux usées se prêtent au pré-traitement anaérobie, qui permet d'améliorer encore la récupération d'énergie de l'ensemble du procédé.

9. Il semble que la digestion anaérobie présente les meilleures possibilités de traitement des eaux usées produites lors du traitement de la tourbe.

1.3 Recommandations

1) Il faudrait faire d'autres travaux de recherche et de développement du procédé de biogazéification de la tourbe avant de pouvoir l'exploiter commercialement. Il y aurait lieu d'accorder la priorité à la recherche et au développement liés aux techniques de pré-traitement et de traitement anaérobie très rapide afin d'améliorer le degré de conversion et les taux de conversion et d'optimiser les coûts.

2) On recommande aussi d'accorder une plus grande priorité aux procédés de carbonisation par voie humide et Wetox, faisant partie du programme de transformation de la tourbe en énergie au Canada, par rapport à la biogazéification à cause de l'état actuel du développement de ces procédés et de leurs avantages économiques relatifs.

1. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

1.1 Summary

ADI Limited was authorized to conduct a study on biogasification of peat by the Department of Supply and Services, Government of Canada in early 1982 as a result of an unsolicited proposal submitted by ADI to the Task Coordinator - Renewable Energy, National Research Council of Canada.

This report presents a review of the literature on biogasification of peat, a discussion of current U.S. research, description of the two promising processes for biogasification, economic analyses of these two processes and an economic comparison with certain other peat utilization schemes. Conclusions derived from this study and recommendations for future course of action related to biogasification are included in this report. An appendix to this report includes an annotated bibliography on the subject.

1.2 Conclusions

The following conclusions were reached after a study and assessment of the processes presently developed for the biogasification of peat.

1. Peat is a mixture of complex substances such as lignin, cellulose, hemicellulose, etc., which all have relatively low, and different degrees of biodegradability; the relative concentrations of these complex substances can vary from bog-to-bog.

2. Biogasification of peat is technically feasible, based on the experimental studies done thus far; pretreatment of the raw peat (in a variety of ways) can significantly improve the biodegradability.

3. Two processes which show promise are i) biogasification using alkaline-oxidative pretreatment developed by Dynatech R/D and ii) BIOTHERMGAS developed by the Institute of Gas Technology (IGT) in the United States.

4. Both processes are in the early phase of development, viz., in the laboratory phase and have not reached the demonstration phase. More developmental work is required for both processes; BIOTHERMGAS has been studied only with respect to other biomass and is thought to be applicable to wet-mined peat. More work is required in order to adapt it to peat.

5. A preliminary economic analysis of these two biogasification processes and comparison with other peat utilization schemes showed that the lowest unit energy cost (exclusive of peat feedstock) was obtained in the Wet Carbonization Process, followed by BIOTHERMGAS Process and Wetox Process, and the highest energy cost was obtained in the Dynatech Process. However, when realistic operation and maintenance costs and scale factors were taken into account, the BIOTHERMGAS Process became less economically attractive. Wet Carbonization and Wetox were still economically quite attractive (with low unit energy cost). This analysis suggests that the production of densified peat may also be economically attractive when done on a large scale. However, one must take into account that this process requires fuel-grade peat feedstock at 50% MC, which has a higher cost than the hydro-peat used in the other processes.

6. From discussions with the Ontario Research Foundation, it was learned that the Wetox Process is ready for demonstration, at a 115 tonne/d capacity, to produce hot water and steam. The Wet Carbonization Process is apparently ready for commercial application according to the U.S. licensee.

7. The environmental impact of the BIOTHERMGAS Process effluent is expected to be minimal, compared to the possible adverse impact of a solubilized effluent from the Dynatech process.

8. The Wetox and Wet Carbonization Processes also generate high-strength wastewaters which should receive treatment before discharge. Laboratory studies have shown these wastes to be amenable to anaerobic pretreatment, which serves to further improve the energy recovery of the overall process.

9. It appears that anaerobic digestion has its greatest potential in treatment of waste streams generated in the processing of peat.

1.3 Recommendations

1) Further research and process development should be done on peat biogasification before this process can be exploited commercially; priority should be given to research and development related to pretreatment and high-rate anaerobic treatment technology to improve the degree of conversion and conversion rates, and to optimize costs.

2) It is recommended that Wet Carbonization and the Wetox Processes be given greater priority in the peat-to-energy programme in Canada in comparison to biogasification because of the relative economics and the present state of development of these processes.

2. INTRODUCTION

The rapidly increasing interest in alternative fuels has focussed attention on peat as one of a number of possible non-conventional energy sources in Canada. In comparison with other peat producing countries, Canada has large resources of peat. According to a recent estimate, the potential/inferred total peatland area in Canada is over 50 million hectares. Measured peat resources in New Brunswick amount to approximately 103 million tonnes (at 50% moisture), occupying an area of about 60 000 hectares.

The microbial bioconversion processes might transform peat into various useful forms of bioenergy such as biochemical, chemical, electrical, luminescent and thermal forms (1)*. One approach to utilizing this vast energy resource is biological gasification (biogasification) of this organic-rich material to methane by anaerobic digestion. This approach merits consideration because of the following factors.

1. Biogasification does not require any dewatering and drying of the high moisture content peat, unlike thermal and thermochemical processes.

2. A peat biogasification process could be ideally coupled to wet harvesting or hydraulic mining (for example, "hydro-peat") techniques.

3. The residue from the process (where only mild forms of pretreatments are done to improve digestibility) can be recycled back to the peat bog or utilized as a soil conditioner.

*Number in parenthesis relates to reference included in Appendix A.

4. Since digested peat is expected to have enhanced dewatering properties, an alternative approach to peat energy conversion by anaerobic digestion of peat followed by gasification of digested dewatered peat to produce SNG appears feasible.

5. The anaerobic digestion process has the ability to accept other available organic feeds (for example, biomass, sewage sludge, industrial waste, in addition to peat).

6. The process has broad application from small to large deposits of peat.

7. The anaerobic digestion technology has been in commercial use for a number of years.

8. The biogasification process may have lesser environmental impact, compared to other processes.

In addition, anaerobic digestion research and development is currently very active in the biomass conversion and waste treatment fields, and it is likely that the new findings in these fields will catalyze the present anaerobic research effort in the peat-to-energy field.

The factors outlined above support the position that biological gasification methods hold great potential for exploitation; methane thus produced from small or large deposits can be piped and distributed within nearby communities or industries for use. However, all of the biological conversion technologies are still in their early development stages.

It was considered necessary to examine the potential of biogasification processes in the peat-to-energy programme in Canada. In this context, ADI Limited submitted an unsolicited proposal entitled, "A Study on Methane Production from New Brunswick Peat by Anaerobic Digestion", January 1982, to the Task Coordinator-Renewable Energy, National Research Council of Canada. This proposal was accepted by the Government of Canada (Supply and Services) with certain amendments vide Contract No. OSX81-00174 dated March 3, 1982; this report on "A Study on the Biogasification of Peat" outlines the work carried out under this contract and presents the results of the study.

3. OBJECTIVES AND SCOPE

3.1 Objectives

The objectives of the study were 1) to identify the recent developments in the area of biogasification of peat for energy production; 2) to examine those biogasification processes in terms of technical and economic feasibility; and 3) to recommend a future course of action related to biogasification in the context of the peat-to-energy programme in Canada.

3.2 Scope of the Study

The scope of the study is presented below as a number of specific tasks to fulfill the objectives indicated above.

Task 1(a) Assemble a source list of the work to date on anaerobic digestion of peat.

(b) Prepare a critical evaluation of the sources listed in (a) and prepare an annotated bibliography.

Task 2 At an appropriate stage of Task 1(b), undertake visits to the two most recent United States Department of Energy (USDOE) research program - Contractors - Institute of Gas Technology (IGT) in Chicago, Illinois, and Dynatch R/D in Cambridge, Massachusetts, to discuss the status of current research and to establish, where possible, the planned future directions of these research efforts.

Task 3(a) Review, on the basis of Tasks 1 and 2, the capital and operating costs of proposed processes, updating published estimates by means of the Consumer Price Index (CPI) and utilize life cycle costing techniques for economic comparison.

(b) Include estimates of process efficiencies and consideration of the disposal of effluent problems and the possible benefication of non-digested residues.

(c) Provide comparison on the same basis with other peat utilization schemes based on data available with ADI and other sources.

Task 4(a) Prepare a draft report outlining the work carried out - literature review, technical and economic feasibility analysis of the biogasification processes, along with recommendations.

(b) Prepare a final report incorporating the feed back from the client.

4. BIOGASIFICATION OF PEAT

4.1 Review of Literature

4.1.1 General

The following data bases were consulted through the Unified Literature Search Service of Canada Institute for Scientific and Technical Information to obtain a list with abstracts, where available, of relevant publications related to the subject.

1.	Chemical Abstracts	1967 to 1981
2.	Coal	1978 to 1981
3.	Engineering Index	1970 to 1981
4.	Energy line	1971 to 1981
5.	Peat Abstracts	1975 to 1981.

Copies of most of the needed publications were obtained from IGT and Dynatech R/D.

4.1.2 A Review of Early Work

The feasibility of methane fermentation of peat was studied in the middle 1920's by a group of Swedish investigators at the Royal Institute of Technology at Stockholm (2). The digestion runs on peat were carried out at mesophilic temperatures between 25°C and 30°C in aqueous media with inoculation of Imhoff tank sludge and horse manure. Results of the study indicated that 1) acid peat inhibited digestion; 2) heated peat was more easily gasified than raw peat; 3) addition of calcium acetate in small quantities increased the rate of methane fermentation; and 4) the total gas yield was less than 0.06 m^3/kg VS (volatile solids) added.

A Russian researcher demonstrated the feasibility of thermophilic methane fermentation of peat in the late 1960's (3). The experiments were conducted at 56°C in a semicontinuous digester operated at a detention time of 10 to 20 days.

4.1.3 A Review of Recent Work

4.1.3.1 Work Done at IGT

Ghosh and Klass (4,5) conducted batch and semicontinuous mesophilic (35°C) and thermophilic (55°C) digestion of Minnesota Reed sedge peat and showed that active peat-digesting cultures could be developed from digested sewage sludge inoculum. These studies indicated that gas yields from peat digestion were low, even at long digester residence times. Methane yields were found to be substantially higher under thermophilic digestion conditions. The highest methane yield of 0.11 std. m^3/kg VS added under a semicontinuous mode of operation was observed at a 55°C digestion temperature, a loading rate of 0.80 kg VS/m^3.d and a residence time of 60 days. Drastic reduction in gas yields occurred when the loading rate was doubled and the residence time was halved.

Further studies (6,7) showed that particle size reduction and acid and alkali treatment of peat enhanced methane production substantially. Results of thermophilic batch studies indicated a 250% increase in methane yield due to particle size reduction alone and a 450% increase due to dilute (3 wt%) NaOH treatment at 132°C and 193 kPa gage. Dilute (8% by weight) HCl treatment resulted in more enhanced hydrolysis and acidification of the peat than any of the other selected pretreatment techniques. Heat treatment alone did not result in any improvement of the peat digestion process.

Semicontinuous digestion of acid-treated peat exhibited the highest methane yield of 0.12 std. m^3/kg VS added at a retention time of 24 days at the thermophilic temperature. This yield corresponds to an energy recovery efficiency of 20% and is three times that of digestion of untreated peat at a comparable retention time of 30 days. Addition of large quantities of sewage sludge (about 50% by weight of the feed on a VS basis) greatly improved methane yield up to 0.29 std. m^3/kg VS added. These studies suggested that additional research should be undertaken to optimize the peat hydrolysis process, digester loading and retention time, bioreactor design and digestion mode, nutrient supplementation and digested peat dewatering. A further discussion of this research is included in Section 4.3.

Another research group at IGT is developing the BIOTHERMGAS process which combines biological and thermal methods for the total conversion of organic feedstocks (biomass, wet-mined peat) to methane. Although evaluations published to date (8,9,10) refer to biomass feedstock, the process is thought to be applicable to wet-mined peat. A description of the process is included in Section 4.2, and a further discussion is available in Section 4.3.

4.1.3.2 Work Done at Dynatech R/D

Dynatech R/D carried out a feasibility study in 1977-1978 for Minnesota Gas Company to determine if biogasification may be a technical and economical process for the conversion of peat into pipeline quality methane (SNG) (11). Preliminary experimental work was done at Stanford University. This study proved that alkaline oxidation pretreatment of peat, with separation of unreacted peat solids and anaerobic fermentation of liquid to methane, would be a technically feasible method for biogasification of peat. In this study, it was estimated that up to 26% of

the energy value in peat was converted to methane in the two-stage process. Based on the results of this study, continued development of the peat biogasification process was carried out by Dynatech R/D for a two-year period through support from US DOE and Minnesota Gas Company.

Results of this study are available in the quarterly progress reports and the final report submitted to US DOE by Dynatech R/D (12,13,14,15) and in other publications (16,17,18). Based on this programme, the solubilization, oxidation and digestion steps have been defined sufficiently through an experimental study to lead to a more reliable process design and preliminary estimate of the fuel gas production costs. The results of this study indicate that biogasification of peat to pipeline quality methane is technically feasible. Further work on 1) continuous solubilization/oxidation studies on peat; 2) alternative alkali pretreatment; and 3) high-rate digestion processes such as anaerobic packed-bed reactors was suggested.

A description of this process is presented in Section 4.2, and a further discussion of this process is included in Section 4.3.

4.2 Description of the Processes

4.2.1 General

There are three biogasification processes under investigation by various research groups. These are:

1) Biogasification using alkaline-oxidative pretreatment developed by Dynatech R/D;
2) BIOTHERMGAS developed by IGT; and
3) Vyrmethane developed in Sweden.

Vyrmethane is a patented, small-scale process which recovers methane generated in situ from recirculating bog water (19,20). Since this is a small-scale process (net chemical energy less than 500 kW), this is not considered further in this evaluation.

More detailed information on this process is available in a recent Ontario Ministry of Natural Resources report (21).

4.2.2 Biogasification Using Alkaline-Oxidative Pretreatment

Figure 1 shows a conceptual process design for a peat biogasification plant developed by Dynatech R/D based on laboratory studies. An overview of the process steps is presented below.

4.2.2.1 Harvesting/Slurry Preparation

Peat is harvested in slurry form by a wet harvesting technique. The peat slurry at 1.5 to 3% solids is pumped to the central processing plant. This slurry is concentrated to 8% total solids through a screening operation before it is sent to the pretreatment reactor.

4.2.2.2 Pretreatment Reactor (Alkaline Oxidation)

The peat slurry is pretreated through a plug-flow staged reactor. In the first stage, peat is partially preheated through a heat exchanger, alkali is injected and peat solubilization occurs. (The peat is hydrolyzed producing many types of substituted phenols.) After solubilization is completed, air is injected into the reactor, and the peat is broken down into fermentable products. (The carbon side chains on the aromatic rings are oxidized into carboxylic and aldehydic functional groups). During pretreatment, a substantial amount of energy is

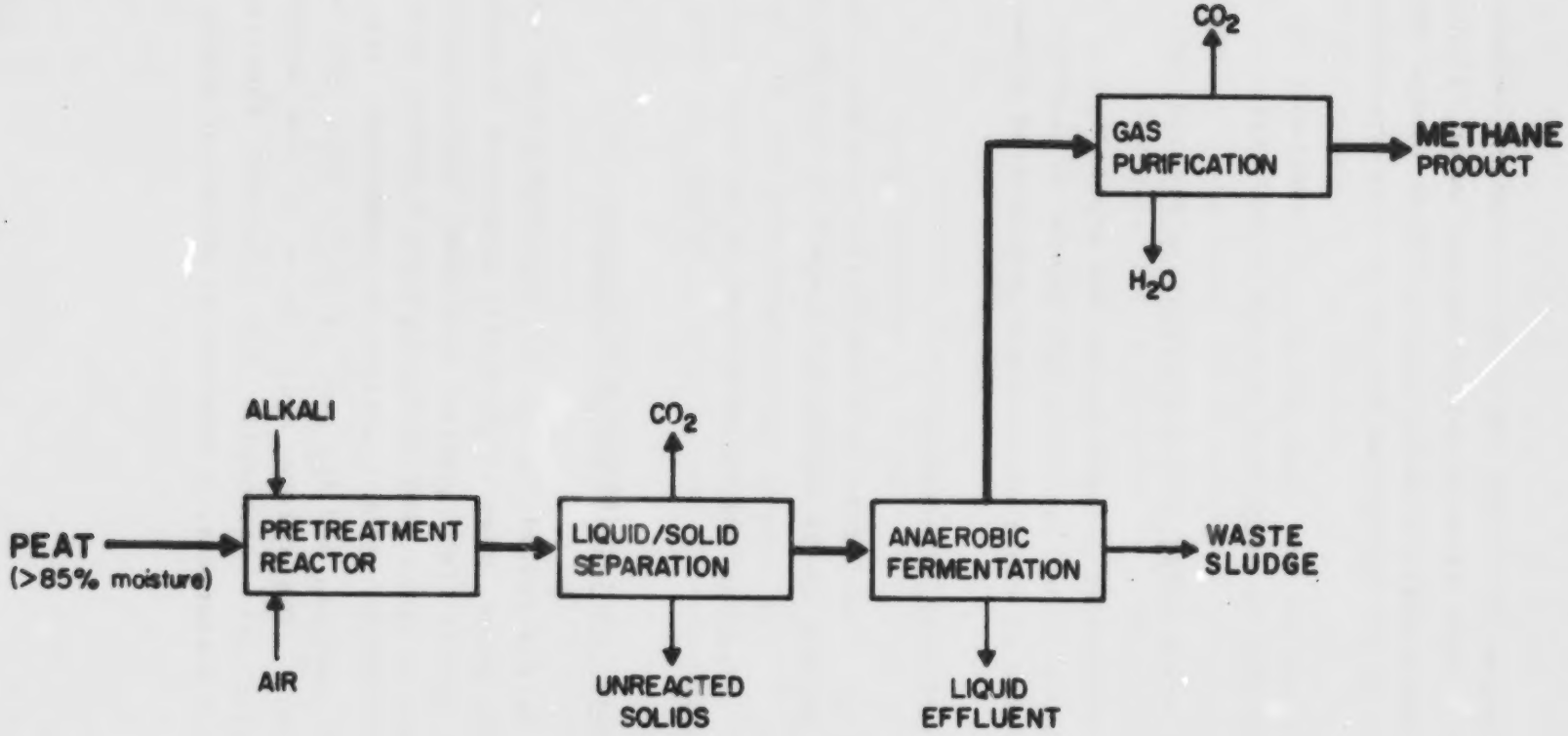

FIGURE I. DYNATECH BIOGASIFICATION PROCESS SCHEMATIC

produced through partial wet oxidation of peat. It is believed that enough heat is produced to keep the pretreatment reactor at the elevated temperature without further energy addition.

4.2.2.3 Liquid Solids Separator

The unreacted peat solids are removed from the pretreated peat slurry by dewatering and can be used as a fuel or returned to the bog. The separated liquid stream flows to the fermentation reactors.

4.2.2.4 Fermentation Reactor

Anaerobic fermentation of the pretreated peat liquors occurs under mesophilic conditions (35°C) in a stirred tank reactor producing methane (60%) and carbon dioxide (40%).

4.2.2.5 Gas Purification Unit

The biogas will contain methane, carbon dioxide, water vapour, and trace amounts of hydrogen sulphide. The gas is scrubbed for removing carbon dioxide and hydrogen sulphide and dried in a dehydration unit. The resulting purified SNG (Substitute Natural Gas) is compressed and is ready for distribution through conventional natural gas pipelines.

It is expected that approximately 43% of the energy value in peat would be converted to methane through this process; the net energy efficiency is estimated to be approximately 33%.

4.2.3 BIOTHERMGAS Process

This process, under development at IGT, combines biological and thermal methods for the total conversion of organic feeds (biomass, wet-mined peat) to methane. Although the experimental and economic evaluations published so far refer to biomass feedstock, the process is thought to be applicable to wet-mined peat.

A generalized process schematic for the BIOTHERMGAS process is shown in Figure 2. Anaerobic fermentation of peat is carried out at 85-92% moisture content, allowing the utilization of wet-mined bog material. The biodegradable component is converted to methane, carbon dioxide and bacterial cells through anaerobic digestion, and the effluent from the digester is mechanically dewatered to a water content of less than 50% and transferred to a thermochemical gasification process. Supernatant from the dewatering process is used to quench the thermal product gases, and for feed, slurry dilution as needed. Dewatered solids are gasified to a mixture of hydrogen, carbon monoxide, carbon dioxide, ammonia and hydrocarbons. Process gases are used for catalytic or biological synthesis of methane. For biological synthesis of methane or biomethanation, the thermally generated gases will be recycled to the digester; this step also provides agitation and heat to the digester. Biomethanation of gases from the gasification of coal by mixed methanogenic cultures has been demonstrated (22).

Direct recycle of the raw synthesis gas eliminates the costly and inefficient steps of water purification and gas upgrading normally associated with thermal gasification. This recycle also provides nutrients in the form of ammonia contained in the gas mixture. Phosphorus can be recovered from the gasifier ash and recycled to the digester.

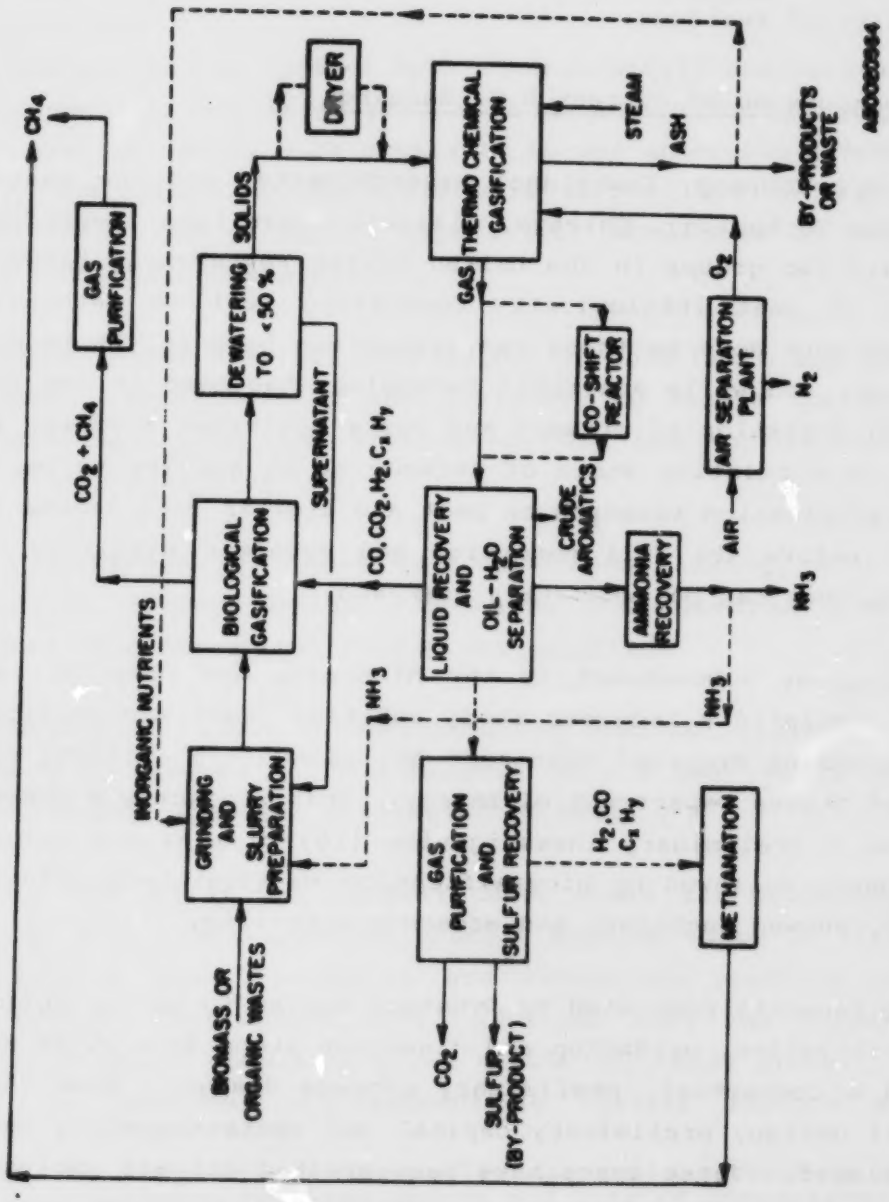

FIGURE 2. IGT BIOTHERMGAS PROCESS SCHEMATIC

Because of the large quantity of waste heat available, it is advantageous to operate the digester at the thermophilic temperature range and achieve higher loading as well as improve dewaterability of residues.

4.3 Discussion of Current U.S. Research

Dynatech R/D Company, Cambridge, Massachusetts, and the Institute of Gas Technology, Chicago, Illinois, have been identified as the only two groups in the United States researching biogasification of peat (biologically converting peat to methane). All of the work done by these two groups has been at the bench-scale level, and while anaerobic technology has been in use for decades on digestion of primary and waste activated sludges, it is still in a relative state of infancy as it applies to peat. More biogasification research on peat and similar feed stocks is necessary before the full potential and economic viability of this technology can be accurately assessed.

Dynatech, under subcontract to the Minnesota Gas Company, has recently completed a two-year study entitled "Peat Biogasification Development Program" (Contract No. DE-AC01-79 ET14696) for the United States Department of Energy. This project was undertaken when a preliminary investigation (10) of alkaline oxidation of peat, followed by biogasification to substitute natural gas (SNG), showed technical and economic viability.

The study recently completed by Dynatech served to better define the solubilization, oxidation and digestion steps from which was developed a conceptual, preliminary process design. From this conceptual design, preliminary capital and operating costs have been developed. These costs have been updated and are included in Section 4.4.2 where they were used to develop unit energy costs for this process.

Dynatech has used reed sedge peat from the Red Lake Region of Minnesota in all of its studies. In its original form, peat is not chemically available to the anaerobic organisms.

Pretreatment in the form of both aqueous alkali and partial oxidation converts the large peat molecules into smaller molecules which are apparently more available to the anaerobic microorganisms. The solubilization steps were carried out in batch type experiments; the oxidation experiments were done in both the batch and continuous modes.

The fermentation step was carried out in both batch and continuous mode. This phase of the study was to assess the ultimate biodegradability of the pretreated peat and to determine the preliminary rate kinetics.

From the results of these experiments and analogy with other substrates, process design assumptions were assembled from which the base case conceptual design was prepared.

On February 25, 1982, a representative from ADI Limited visited Dynatech to discuss various aspects of its peat study and any planned future research activities on peat.

At this meeting it was learned that, while the projected unit SNG cost from the conceptual process appears to be in line with other fuels, cost reductions are definitely possible through more process development work. Further work and research is needed; priority should be given to the following areas:

1. chemical pretreatment to further improve methane conversion;
2. investigate alternative anaerobic technology to increase both the degree and rate of conversion;
3. dewatering technology (for unsolubilized peat); and
4. chemical recovery.

At this meeting with Dynatech, the process design assumptions used in development of the conceptual design and preliminary economics were discussed briefly. It would appear that all of these assumptions are realistic through additional process refinements and research. The only assumption which could be somewhat optimistic is that of the 67% mesophilic conversion of fermentables at 20 days retention time. Dynatech suspects inhibition from sodium ions and the lack of electron acceptors as reasons for the low degree of conversion they experienced in the laboratory.

From data presented by Dynatech, it would appear that the rate of digestion has to increase greatly (approximately 8 times) to achieve 67% conversion in 20 days. It remains to be seen if this increase can be achieved through additional research in areas 1, 2 and 4 listed above.

At the present time, Dynatech has no research funds to conduct further work on peat biogasification. However, it is carrying out research into the production of liquid fuels and chemicals from organic acids. These acids are the product of the anaerobic acid formation of peat. It is believed that the economics for liquid fuels via the organic acid route will be better than SNG from peat biogasification.

Researchers at the Institute of Gas Technology have been very active in the field of peat (and other feedstock) to energy conversions. The conversion technologies with which these researchers have worked, and are developing, include biogasification, thermal gasificaton, wet carbonization and hybrid systems using more than one of these technologies to improve the net energy output.

Dr. Ghosh of IGT has been the most active researcher at IGT in the field of biogasification. He favors the biogasification approach with peat as it has direct application to hydro-peat, thus eliminating costly dewatering and dehydration steps.

Dr. Ghosh's biogasification work, to date, has all been at the bench-scale level. His research on Minnesota Reed Sedge Peat began in 1975 and has proceeded in four major phases; viz., feed characterization, batch digestion experiments, semicontinuous digestion and investigations of pretreatments to improve peat digestibility. The pretreatment of peat included size reduction (to indicate particle size effect) and acid/alkali treatment at elevated temperature and pressure to improve its biodegradability.

Ghosh has identified several problems which may limit and/or reduce the anaerobic digestion of peat; these are:

1. peat contains substantial amounts of compounds which are resistant to anaerobic digestion, and it is in a partially carbonized form which limits its availability to microorganisms;
2. a nutrient deficiency may occur with some of the essential elements which are organically bound; and
3. inhibitory effects of nitrates, sulphates and antibiotics contained within the peat itself.

Ghosh's data suggests that satisfactory digestion can be maintained on peat at both thermophilic and mesophilic ranges. However, methane yields were significantly less at the mesophilic temperature and decreased dramatically for both temperature ranges when the digester retention time was halved from 60 to 30 days. Ghosh also found that particle size reduction and alkali and acid treatment of the peat increased methane production markedly. Heat treatment of the peat alone did not produce any noticeable beneficial effect.

Acid treated peat showed the largest methane yield at a detention time of 24 days, operating at 55°C. This methane yield corresponded to a thermal efficiency of 20% and was three times higher than for untreated peat at similar digestion conditions. Ghosh's data also suggests that the digested peat slurries have enhanced dewatering characteristics.

Again, as with Dynatech's work, further research in the area of biogasification of peat is required to optimize various process steps before the potential and economics of the process can be accurately and fully assessed.

Two of the major limitations of the biogasification process (at least as perceived today) as it particularly relates to peat and other similar material, are, firstly, much of the peat may be refractory to digestion and secondly, there appears to be a nutrient deficiency because some of the essential elements are organically bound.

The above and other limitations have resulted in the researchers (Chynoweth et al) at IGT developing a process called BIOTHERMGAS. This process combines both biogasification and thermochemical gasification steps to create a process with complete conversion of any biomass feedstock to SNG. The effectiveness of this process is, apparently, not affected by nutrient and feedstock water content. A schematic and description of this process are presented in Section 4.2 above. This process concept has application to a wide spectrum of feedstocks, decreases the process liquid and solid residues, and can markedly increase the thermal efficiency of the total system. Critical to the success of this process is the dewatering of the digester effluent prior to thermochemical gasification; a total solids level of greater than 40% is needed to make the process viable. Methanation of

the synthesis gas can be accomplished via biomethanation or catalytically. The preferred route is biomethanation.

Peat has not been used as a feedstock in this process, to date. However, the process is thought to be readily adaptable to hydro-peat.

IGT has developed capital and operating costs for the BIOTHERM-GAS Process using feedstocks such as Bermuda Grass. These costs have been used in Section 4.4.3 below to develop a unit energy cost for the process. It is believed that these capital and operating costs will be similar to that for peat.

On February 24, 1982, a member of ADI's engineering staff met with Dr. Ghosh and Dr. Chynoweth to discuss their past and present research activities with peat and other feedstocks.

As was the case at Dynatech, Dr. Ghosh felt it necessary to do further research in the area of peat biogasification, especially in the areas of pretreatment optimization and high rate anaerobic technology. IGT is presently investigating these high rate technologies in such areas as industrial wastewater treatment.

Dr. Chynoweth felt that he would like to do more research in areas relating to thermal gasification, biomethanation of synthesis gas (product of the thermochemical gasification step) to SNG and to carry out more detailed economic analysis of the BIOTHERMGAS Process.

It was also learned that much of the research on biogasification and the BIOTHERMGAS Process has been funded in-house, and at present, there are no funds available for work with peat.

As a final remark, it should be pointed out that all of the activities of IGT discussed above have only been done at the bench-scale level. In the case of the BIOTHERMGAS Process, IGT have not, as yet, a complete, workable bench-scale system. To date, they have only looked at the biogasification and thermochemical gasification steps in isolation and feel there will be little difficulty in interfacing these unit processes.

4.4 Process Plant Economics

4.4.1 General

The cost estimates presented in this report are based upon estimates developed elsewhere; Table 4.1 presents a listing of the information sources used.

Because of the diverse origins of the estimates in terms of methods, purpose, and date, considerable effort was expended to put the estimates on an equal basis suitable for comparison purposes. Listed below are the assumptions which were used to develop the costs.

1. All the costs are in Canadian dollars.
2. The rate of exchange between American and Canadian dollars was assumed to be $1.00 Canadian = $0.80 American .
3. All the costs are for July 1, 1982.
4. An interest rate of 12% was used.
5. A 15-year life was assumed for each process plant.
6. Each plant was assumed to have been constructed instantaneously (i.e., no interim financing).
7. No allowance was made for cost inflation.
8. Each plant was assumed to have zero salvage value.
9. The cost of the peat feedstock was assumed to be zero.
10. Capital costs were updated using a CPI value for annual inflation of 12%.

TABLE 4.1

INFORMATION SOURCES USED IN DEVELOPING COST ESTIMATES

	COST ESTIMATE	SOURCES
1.	Dynatech Biogasification	"Peat Biogasification Development Program," a report prepared by Dynatech Corp. of the United States Dept. of Energy, April 21, 1981 (15) "Peat in Ontario" (21)
2.	IGT "Biothermgas"	"Peat in Ontario (21)
3.	Wet Carbonization	"Peat in Ontario (21)
4.	Densified Fuel Peat	ADI File No. 1787-13
5.	Wetox Process	Personal communication with J. Sheppard of the Ontario Research Foundation

Several potential weaknesses inherent in the cost data utilized should be realized. Firstly, the estimates varied greatly in level of supporting detail, with some estimates having limited information available as to the components of the costs provided, while others were itemized in some detail. Secondly, the battery limits of the projects varied substantially; for example, wastewater treatment was not considered in all capital cost estimates. For some estimates it was not known what the exact battery limits were. Thirdly, there were large variations in the scale of the projects reviewed. Some projects were as much as two orders of magnitude larger than others. This difference penalized the unit costs of the smaller projects because of the economics of sale associated with the larger projects. Fourthly, the capacities of the plants studied were based upon different estimates of operations time ranging from 250 to 360 days per year (see Table 4.11).

For each plant, a capital cost and an annual cost estimate is provided. The annual cost includes the operations and maintenance cost and the amortization expense. This annual cost can then be divided by the annual energy production figure to determine the estimated comparative unit energy cost for the project. This unit cost can be used for comparisons among the various peat projects and with other energy schemes.

4.4.2 Dynatech Process

The capital and operating costs for the conceptual, peat biogasification process put forth by Dynatech (reference Section 4.2 for process description) were developed on the basis of the "base case design process assumptions" listed in Table 4.2. The base case conceptual plant has a processing capacity of approximately 7 600 tonnes of dry peat per day and an energy output in the form of SNG of approximately 71.4 TJ/d (67.7 x 10^9 Btu/d);

TABLE 4.2

DYNATECH BIOGASIFICATION PROCESS BASE CASE DESIGN PROCESS ASSUMPTIONS

PROCESS STEP	ASSUMPTIONS
Slurry Preparation	3% Solids Feed 8% Solids Output
Pretreatment-Solubilization	Plug Flow Reactor 90% conversion 0.3 kg Na_2CO_3/kg peat 150°C
Oxidation	Plug Flow Reactor 90% conversion 0.4 kg O_2/kg solubilized product converted 150°C 0.024 h retention
Heat Exchanger	10°C Inlet Slurry Temperature 37°C Exit Temperature for Feed to Digester
Liquid/Solids Separation	Undissolved Solids Separated to 25% Solids
Digestion	CSTR 37°C 20 day retention time 67% conversion of fermentable products Gas Composition, 60% CH_4/40% CO_2
Gas Purification	3% CO_2 Concentration in Purified Gas 6.89 MPa Output Pressure Power Requirement of 7.9 W/m^3 SNG

From: Reference 15, 18, 21

the projected net thermal efficiency of the process is approximately 33%. The feedstock to the base case plant is wet-harvested peat at 3 percent solids. The projected mass and energy balances appear in Tables 4.3 and 4.4, respectively.

The projected mid-1982 capital and operating costs appear in Tables 4.5 and 4.6, respectively.

The projected capital cost for the Dynatech Process is $304 900 000; the projected annual operating cost is $185 000 000.

The projected unit energy cost for the SNG produced is $7.20/GJ.

The costs for the Dynatech Process are quite detailed, especially considering the experimental nature of the process. It should be noted that the wastewater treatment cost has not been included in the estimate. The major capital cost items are the digestors (45% of total), pumps and pipes (8%) and liquid/solids separation (4%). Non-equipment items such as start-up (11%) and contingencies (11%) appear to be adequately covered in the capital cost estimate.

Annual cost items of note are Na_2CO_3 (41%), electricity (16%) and amortization (23%). Labour accounts for 7% of the annual costs of this project.

Dynatech carried out an analysis to examine the sensitivity of the unit energy cost to changes in process variables. This analysis revealed that variables having the greatest influence on the waste energy costs are digester retention time, slurry concentration and alkali pretreatment costs. Another factor which would also influence the unit cost significantly is the

TABLE 4.3

DYNATECH BIOGASIFICATION PROCESS MASS BALANCE

Feed to Process	tonnes/day
Raw peat (dry basis, 90% volatiles)	7 590
Sodium carbonate	2 182
Oxygen	2 273
Outputs from Process Step	
Solubilization	
Dissolved peat	6 145
Undissolved peat	682
Ash	764
Sodium carbonate	2 182
Oxidation	
Fermentables	4 700
Undissolved peat	682
Ash	764
Sodium carbonate	2 182
Dewatering	
Fermentables	4 564
Ash	736
Sodium carbonate	2 109
Digestion	
Fermentables	1 518
Ash	736
Sodium carbonate	2 109
Gas Purification	
Methane	1.896×10^6 m^3/d (71.4 TJ/d)

From: Reference 15

TABLE 4.4

DYNATECH BIOGASIFICATION PROCESS ENERGY BALANCE

PROCESS STEP	ENERGY (INPUT) OUTPUT/DAY
Pretreatment-oxidation (28 600 hp)	(5.7 TJ)*
Solids/liquids separation (12 500 hp)	(2.4 TJ)*
Digestion (12 000 hp)	(2.3 TJ)*
Gas purification (33 000 hp)	(6.6 TJ)*
Energy in methane	71.4 TJ
Net energy output	54.4 TJ
Energy in peat	162.5 TJ
Net energy efficiency $\frac{54.4 \times 100}{162.5}$	33%

*assuming electrical power conversion efficiency of 32.5%

From: Reference 15, 18, 21

TABLE 4.5

DYNATECH BIOGASIFICATION PROCESS
BASE CASE CAPITAL COSTS (1)

		1982 $
A.	EQUIPMENT AND STRUCTURES	
1.	Slurry preparation	100 000
2.	Pretreatment - solubilization	100 000
	- oxidation	1 900 000
3.	Heat exchanger	3 300 000
4.	Liquid/solids separation	12 000 000
5.	Digesters	140 000 000
6.	Gas purification	9 800 000
7.	Pumps, piping, electrical, instrumentation	22 800 000
8.	Support facilities (5% of above)	13 900 000
9.	Wastewater treatment	NIC
	Subtotal	203 900 000
B.	OTHER COSTS	
1.	Contractor's overhead and profit @ 10% of A	20 400 000
2.	Engineering and design @ 5% of A	10 200 000
3.	Contingencies @ 15% of A + B1 + B2	35 200 000
4.	Start-up @ 15% of A + B1 + B2	35 200 000
5.	Working capital, interest during construction	NIC
	TOTAL	$304 900 000

(1) Based on December 1980 costs and assumed annual inflation rate of 12% until July 1, 1982.

TABLE 4.6

DYNATECH BIOGASIFICATION PROCESS
BASE CASE ANNUAL COSTS (1)

		1982 $
A.	AMORTIZATION @ 12% for 15 years CRF = 0.14682	$ 44 800 000
B.	RAW MATERIALS AND SUPPLIES	
1.	Peat	NIC
2.	Na_2CO_3	76 000 000
3.	Supplies - operating	1 300 000
	- maintenance	5 800 000
C.	UTILITIES	
	- Electric ($0.05/kWh)	28 100 000
D.	LABOUR	
	- Operating	4 500 000
	- Maintenance	5 800 000
	- Supervision	1 600 000
E.	ADMINISTRATION AND OVERHEAD	7 100 000
F.	LOCAL TAXES AND INSURANCE	10 000 000
	TOTAL	$185 000 000
	Net Energy Cost	$7.20/GJ

(1) Based on December 1980 costs, updated at 12% annual inflation until July 1, 1982.

degree of conversion. Factors which positively affect the above parameters should receive priority in any future research work in this area.

4.4.3 BIOTHERMGAS Process

IGT has done a preliminary economic analysis of its BIOTHERMGAS Process for at least two feedstocks, viz., Bermuda Grass and municipal solid wastes. The economic analysis for Bermuda Grass with a thermophilic digestion step is presented here. Details of the process are presented below in Table 4.7. The characteristics of Bermuda Grass are shown on Table 4.8.

The conceptual plant has a capacity of 9 090 dry tonnes per day of Bermuda Grass. The daily energy output, in the form of SNG, is approximately 123.0 TJ, yielding a cold gas efficiency of 72%.

The projected, mid-1982 capital and annual costs are presented below in Tables 4.9 and 4.10, respectively. The projected capital cost for the conceptual system is $587 000 000; the projected annual cost is $115 600 000. The projected unit energy cost is $3.00/GJ.

The costs for the BIOTHERMGAS Process are relatively detailed, although not as fully described as those for the Dynatech Process. Items not explicitly covered in the capital cost table include pumps, pipes, support facilities and wastewater treatment. However, it is likely that the former two are included under the various equipment headings.

TABLE 4.7

BIOTHERMGAS PROCESS SYSTEM DETAILS

Feed	- Bermuda Grass
Feed input	- 9 090 dry tonnes per day
Digestion	
Temperature	- 55°C
Reactor volume	- 0.72 x 10^6 m^3
Loading	- 12.0 kg VS/m^3.d
Retention time	- 7 days
Assumed methane yield	- 0.25 m^3/kg VS added
Digester gas	- 60/40 mole % CH_4/CO_2
Gasifier	
Single-stage reactor	
Temperature	- 980°C
Pressure	- 345 kPa
Carbon conversion	- 99%
Solids residence time	- 10-20 min.
Methanation of synthesis gas	- Biomethanation
SNG output	- 122.9 TJ/day
Cold gas efficiency*	- 72%
Total plant efficiency	- 80%

*Cold gas efficiency = SNG energy/feed energy

TABLE 4.8

CHARACTERISTICS OF BERMUDA GRASS

Total moisture, % by wt.	33.0
Total solids, % by wt.	67.0
Volatile solids, % dry wt.	95.0
Ash, % dry wt.	5.0
Heating value MJ/kg	19.0
Total carbon, % dry wt.	47.1
Total hydrogen, % dry wt.	6.04
Total oxygen, % dry wt.	39.4
Total nitrogen, % dry wt.	1.96
Total sulfur, % dry wt.	0.21

From: Reference 8

TABLE 4.9

IGT BIOTHERMGAS PROCESS BASE CASE CAPITAL COSTS (1)

		1982 $
A.	EQUIPMENT AND STRUCTURES	
1.	Feed preparation	$ 58 000 000
2.	Digestors	130 000 000
3.	Dewatering	55 000 000
4.	Gasifiers	72 000 000
5.	Heat exchangers	14 000 000
6.	Liquid recovery	14 000 000
7.	Gas purification	65 000 000
8.	Oxygen plant	43 000 000
9.	Pumps, piping, electrical, instrumentation	INCL. ABOVE
10.	Support facilities	INCL. ABOVE
11.	Wastewater treatment	NIC
	Subtotal	$451 000 000
B.	OTHER COSTS	
1.	Contractors overhead and profit (incl. in A)	---
2.	Engineering and design (incl. in B3)	---
3.	Start-up, contingencies @ 30% of A	136 000 000
4.	Working capital, interest during construction	NIC
	TOTAL	$587 000 000

(1) Based upon December 1980 costs, updated at 12% annual inflation until July 1, 1982.

TABLE 4.10

IGT BIOTHERMGAS PROCESS BASE CASE ANNUAL COSTS(1)

		1982 $
A.	AMORTIZATION @ 12% for 15 years CRF = 0.14682	$ 86 200 000
B.	RAW MATERIALS AND SUPPLIES	
1.	Peat	NIC
2.	Other materials (incl. in D)	---
C.	UTILITIES (Incl. in D)	---
D.	LABOUR (Incl. Maintenance) 5% of capital	29 400 000
E.	ADMINISTRATION AND OVERHEAD (Incl. in D)	---
F.	LOCAL TAXES AND INSURANCE (Incl. in D)	---
	TOTAL	$115 600 000
	Unit Energy Cost	$3.00/GJ

(1) Based upon December 1980 costs, updated at 12% annual inflation until July 1, 1982.

Major items in the capital cost estimate are digesters (20%), gasifiers (12%), gas purification (11%), feed preparation (10%) and dewatering (9%). Non-equipment costs are lumped together in one sum which is 30% of equipment cost; this is comparable to that for the Dynatech Process.

Annual costs are much less detailed. The maintenance figure presented here represents only 5% of capital cost which seems very low when compared to the 22% figure in the Dynatech estimate. (The latter does not include the Na_2CO_3 cost.)

4.5 Economic Comparison With Other Peat Processes

In the previous section, the unit energy costs were developed for the Dynatech Biogasification and BIOTHERMGAS Processes. The unit energy costs for the Dynatech and BIOTHERMGAS systems were $7.20/GJ and $3.00/GJ, respectively (exclusive of peat feedstock cost).

In Table 4.11 below, the projected unit energy costs for the above systems are compared to those of other technologies including Densified Peat, Wetox and Wet Carbonization. Figures 3 and 4 show the schematics of Wetox and Wet Carbonization Processes, respectively.

The unit energy costs for densified fuel peat is $4.90. This cost was developed from previous work done at ADI Limited. The output from this facility is relatively small being 25 500 tonnes per annum at 10% MC (1.9 TJ/d).

The capital and annual costs used to develop the unit energy cost appears below in Tables 4.12 and 4.13.

TABLE 4.11

COMPARISON OF PROJECT UNIT ENERGY COSTS

PROCESS OR FUEL	PLANT CAPACITY tonnes/day, dry peat	PLANT OUTPUT	UNIT COSTS[1] per GJ
Dynatech	7 590[2]	71.4 TJ/d as SNG	$7.20[3]
BIOTHERMGAS	9 090[2]	123.0 TJ/d as SNG	3.00[4]
Densified peat	94	1.9 TJ/d (as briquetted peat @ 10% MC)	4.90[5]
Wet Carbonization	975	14.5 TJ/d (as PDF @ 8% MC)	2.12[6]
Wetox	115[2]	1.4 TJ/d (as hot water and steam)	3.76[7]

1. feedstock cost not included.
2. assumed to be 100% plant capacity.
3. assuming 100% plant capacity for 360 d/a operation.
4. assuming 100% plant capacity for 312 d/a operation.
5. assuming 100% plant capacity for 250 d/a operation.
6. assuming 100% plant capacity for 291 d/a operation.
7. assuming 100% plant capacity for 330 d/a operation.

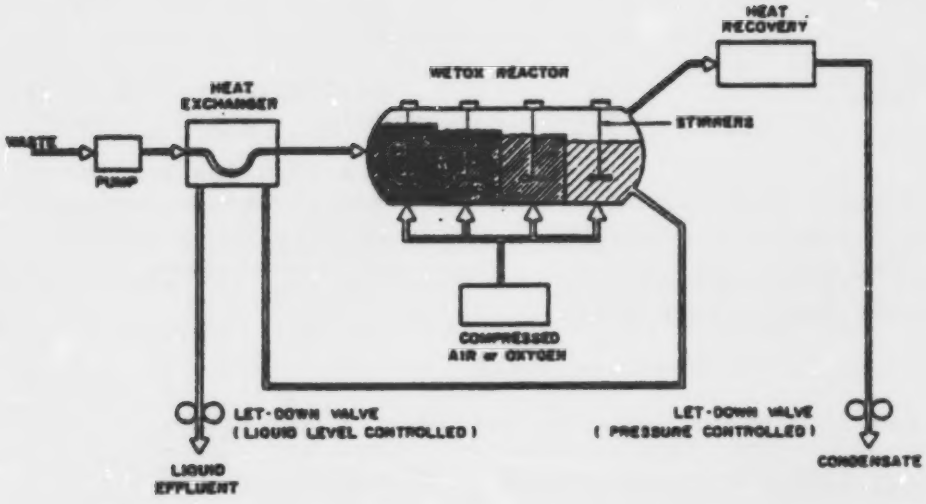

FIGURE 3. WETOX$^{(R)}$ PROCESS SCHEMATIC

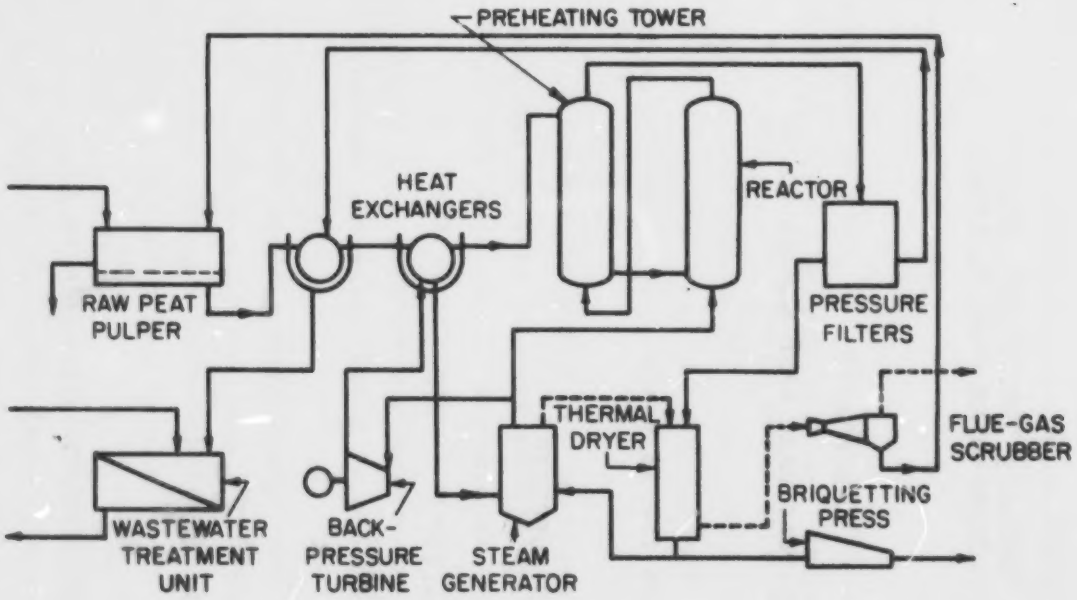

FIGURE 4. SIMPLIFIED PROCESS FLOW DIAGRAM FOR THE PEAT WET CARBONIZATION PROCESS

TABLE 4.12

DENSIFIED FUEL PEAT BASE CASE CAPITAL COSTS(1)

Capital Cost in 1982 $ = $5 900 000

(1) Based upon February 1982 costs, updated at 12% annual inflation to July 1, 1982.

TABLE 4.13

DENSIFIED FUEL PEAT BASE CASE ANNUAL COSTS(1)

		1982 $
A.	AMORTIZATION @ 12% for 15 years CRF = 0.14682	$ 870 000
B.	RAW MATERIALS AND SUPPLIES	
1.	Peat	NIC
2.	Dies and roll shells	180 000
3.	Equipment maintenance	160 000
C.	UTILITIES	
	- electric (0.05/kWh)	560 000
D.	LABOUR	300 000
E.	ADMINISTRATION AND OVERHEAD (@ 10% A to D)	210 000
F.	LOCAL TAXES AND INSURANCE (Incl. in E)	---
	TOTAL	$2 300 000
	Unit Energy Costs	= $4.90/GJ

(1) Based upon February 1982 $, updated at a 12% annual inflation rate to July 1, 1982.

The capital cost estimate contains very limited information. The cost total has not been broken down into items and, thus, it is impossible to determine the battery limits of this project.

The annual cost estimate is quite detailed. Annual operating costs are equal to 24% of capital cost. Major items of the estimate are amortization (39%), utilities (25%), labour (14%) and administration (9%).

The unit energy cost for the Wet Carbonization Process ($2.12) was derived from the capital and annual costs presented in Tables 4.14 and 4.15. These costs were developed from cost data presented in Reference 20. The production and energy output from this facility are 200 000 tonnes PDF/a and 14.5 TJ/d, respectively.

Very little detail is available on these cost estimates. This is unfortunate as this process is now being offered for sale for use in full-scale plants. The operations and maintenance cost given is equal to 7.5% of capital cost. This seems low, but the technology of this process appears to be less complex than that of the Dynatech and BIOTHERMGAS Processes.

The projected Wetox unit energy cost was found to be $3.76/GJ as presented in Table 4.11 earlier. This unit cost was developed from cost data through personal communication with J. Sheppard of the Ontario Research Foundation.

Capital and annual cost data for the Wetox system appear in Tables 4.16 and 4.17. The capital cost does not include an allowance for waste treatment.

TABLE 4.14

WET CARBONIZATION PROCESS BASE CASE CAPITAL COSTS(1)(2)

Capital Costs in 1982 $ = $40 730 000

(1) Includes all installations within battery limits, waste water treatment, civil works, construction management, engineering, working capital and start-up.

(2) Based on July 1, 1981 costs, updated at 12% annual inflation to July 1, 1982 costs

TABLE 4.15

WET CARBONIZATION PROCESS BASE CASE ANNUAL COSTS(1)

		1982 $
A.	AMORTIZATION @ 12% for 15 years CRF = 0.14682	$5 980 000
B.	RAW MATERIALS AND SUPPLIES	
1.	Peat	NIC
2.	Other supplies (incl. in D)	---
C.	UTILITIES (Incl. in D)	
D.	LABOUR (and Maintenance)	3 000 000
E.	ADMINISTRATION AND OVERHEAD (Incl. in D)	---
F.	LOCAL TAXES AND INSURANCE (Incl. in D)	---
	TOTAL	$8 980 000
	Unit Energy Cost	= $2.12/GJ

(1) Based on July 1, 1981 costs, updated at 12% annual inflation to July 1, 1982.

TABLE 4.16

WETOX PROCESS BASE CASE CAPITAL COSTS(1)

Capital Costs in 1982 $ = $5 640 000

(1) Based on January 1981 costs, updated at 12% annual inflation to July 1, 1982.

TABLE 4.17

WETOX PROCESS BASE CASE ANNUAL COSTS(1)

		1982 $
A.	AMORTIZATION @ 12% for 15 years CRF = 0.14682	$ 828 000
B.	RAW MATERIALS AND SUPPLIES	
1.	Peat	NIC
2.	Other supplies (incl. in C)	---
C.	UTILITIES	280 000
D.	LABOUR	630 000
E.	ADMINISTRATION AND OVERHEAD (Incl. in D)	---
	TOTAL	$1 738 000
	Unit Energy Cost	= $3.76/GJ

(1) Based on January 1981 costs, updated at 12% annual inflation to July 1, 1982.

The lowest unit cost belongs to the Wet Carbonization Process, followed by the BIOTHERMGAS Process; the most expensive process is the Dynatech Process. The other two processes are midway between the high and low values.

Because of the four problems of detail, battery limits, scale and operations time described in Section 4.4.1, the unit cost estimates are not directly comparable. However, the differences between the alternatives are large enough that by qualitatively accounting for these problems, conclusions can be drawn.

It should be noted that the processes with the most comprehensive breakdown detail in annual operating cost estimates (viz., Dynatech, Densified Peat, and Wetox) also had the highest annual operating costs, both in terms of unit costs and as a percentage of capital cost (16-24%). This would seem to indicate that the other two processes have understated annual cost figures (3-7.5%). If annual operating costs were set at 20% of the capital cost, the unit values of the BIOTHERMGAS and Wet Carbonization Processes would increase by approximately 75% and 60%, respectively (see Table 4.18).

Experience suggests that differences in battery limits which exist in the capital cost would account for only a 10% increase in capital cost and, consequently, only about 5% in the annual and unit energy costs. The effect of these omissions, therefore, is believed to be minor and will be ignored.

The smallest two projects are the Wetox and Densified Fuel Peat Project which are about the same size; the next largest project is the Wet Carbonization Process which is about 10 times as large as the smallest two, and the two largest projects are the Dynatech and BIOTHERMGAS Processes which are about 100 times as the smallest two.

Such large differences in relative plant size will affect the accuracy of comparisons of the unit costs of production among the five processes.

In order to examine the effects of plant size upon process costs, adjustments were made to the costs of the various projects. All five projects were evaluated for a plant size of 2 000 dry tonnes of peat input per day. A scaling factor* of 0.7 was used to adjust project capital costs. However, many annual costs tend to vary linearly with changes in size (i.e. raw material prices) while others (i.e. amortization) vary according to the scale factor. Unfortunately, the lack of detail in the annual cost estimates utilized from previous studies made it impossible to differentiate between the two types of costs (linear and scaled); therefore, annual costs were analyzed twice. In Case 1, the scale factor was applied to only amortization costs while the operations and maintenance costs were scaled linearly. In Case 2, the scale factor was applied to amortization costs, and the operations and maintenance costs were set at 20% of the (scaled) capital costs. The probable annual and unit costs for the 2 000 tonne plant would lie somewhere between the two estimates obtained under Case 1 and 2. For both analyses, the cost of Na_2CO_3 for the Dynatech project was scaled linearly.

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*Scaling factors can be used to correlate the equipment costs of different size projects. The factor can range in value from 0.2 to 1.0 depending upon the type of equipment used and other factors. A value of 0.7 is often used for chemical and energy projects. The factor is used as follows: $C_A = C_b \left(\frac{La}{Lb}\right)^X$

where: C_A = cost of equipment in plant a
C_b = cost of equipment in plant b
La = capacity of equipment in plant a
Lb = capacity of equipment in plant b
X = scale factor

Equipment costs affect capital cost, amortization expense and operation and maintenance expenses.

The effects of these adjustments are roughly quantified in Table 4.18. The table illustrates the cost advantages of the Wetox, Wet Carbonization and Densified Peat alternatives. Note that under both Case 1 and Case 2, the unit costs of the BIOTHERMGAS Process have increased from second lowest to second highest. It should also be noted that the Densified Peat Process is actually less attractive than shown here because it has a higher valued feedstock, viz., milled fuel peat at 50% moisture.

4.6 Environmental and Other Considerations

Of the different technologies discussed in this report, the Dynatech Process would have the most adverse environmental impact. In the Dynatech process, a large percentage of the peat solids are solubilized and oxidized prior to digestion. A high percentage of these organics (33% of digester feed) are apparently refractory and remain in the final effluent along with the sodium carbonate added in the pretreatment step. Since this organic material is now in the dissolved form, it is mobile and should not be returned to the bog. If this is done, it may eventually affect water supplies, etc. The only reasonable place to discharge this effluent would be a rather large receiving body of water where its impact will be negligible.

Approximately 9% of the peat feedstock remains undissolved in the Dynatech Process and is removed in the dewatering step prior to digestion. If these solids can be further dewatered to 50% solids, they can be burned on-site for space heating requirements, etc.; alternatively, these solids can be discharged into the raw peat slurry water and returned to the bog. The impact in the bog should not be significant except for the alkali content which would increase to some equilibrium level. This equilibrium level would be a function of weather patterns and dilution by fresh water entering the bog.

TABLE 4.18

EFFECTS OF ANNUAL COST ADJUSTMENTS UPON UNIT COSTS

PROCESS	ORIGINAL UNIT COST	UNIT COST WITH O & M COST = 20% OF CAPITAL COST	UNIT COST WITH SCALE FACTOR CASE 1*	CASE 2**
Dynatech	$7.20	$7.10	$8.00	$9.10
BIOTHERMGAS	3.00	5.30	4.30	8.40
Densified peat	4.90	4.30	2.40	1.20
Wet Carb.	2.12	3.40	1.50	2.20
Wetox	3.76	4.20	2.70	1.80

*Amortizaton scaled, operations and maintenance costs increased linearly.

**Amortization scaled plus operations and maintenance costs at 20% of scaled capital cost.

One will have to deal with fairly strong effluents from both the Wetox and Wet Carbonization Processes. Anaerobic treatment has been investigated for both of these systems. In addition to effluent treatment, anaerobic digestion of the effluent further improves energy recovery for the overall process. For the case of the Wet Carbonization Process by Wheelabrator-Frye, the wastewater treatment system included for in the capital costs, also includes aerobic treatment. This treatment process is said to provide a final effluent equivalent to pulpmill effluent standards. It may be possible to discharge this final effluent into the bog if there is sufficient dilution.

The BIOTHERMGAS Process will not likely present any significant environmental impacts. It is felt that the supernatant from the dewatered digester effluent should be fairly innocuous, as there is no pretreatment given to the peat digester feed. Therefore, this effluent will contain only low levels of unconverted volatile acids, unutilized nutrient compounds and those undigested materials in the original peat. If the bog will provide any amount of dilution, the environmental impact should be acceptable.

5.0 RECOMMENDATIONS FOR FUTURE WORK

In Section 4.5, an economic comparison of the different peat processes considered herein was made on the basis of unit energy costs, exclusive of the peat feedstock price. This basis of comparison is justifiable in these circumstances where only global economics are being used to determine the potential economic viability of a process.

After an allowance for scale, the processes which emerged from the analysis with the projected lowest unit costs were Wetox and Wet Carbonization.

The Wet Carbonization Process discussed herein is licensed to Wheelabrator-Frye, an American firm, and is ready for commercial exploitation. Wheelabrator-Frye has determined that there is market potential for this type of peat-derived fuel and has plans to build a full-scale demonstration plant in the Northeastern United States in the near future.

Developers of the Wetox Process, the Ontario Research Foundation (ORF), have an ongoing research program (under sponsorship of Canmet Energy Research Laboratores) to investigate two processes utilizing its Wetox technology on wet-mined peat (hydro-peat). One of the processes involves only the generation of steam and hot water for thermal energy applications, and the second process is the wet carbonization of peat through partial oxidation in the Wetox Process. After partial oxidation, the peat slurry can be dewatered to greater than 50% solids content. This latter process is similar to the Wet Carbonization Process

licensed by Wheelabrator-Frye. The objective of ORF is to develop sufficient design criteria to determine the technical and economic viability of the above processes in Canada.

The unit energy cost figure in comparison to the others suggests that the Wetox Process, for the generation of hot water and steam, could have commercial potential. It should be noted that anaerobic treatment of the Wetox effluent may improve the overall thermal efficiency significantly. This may effect a lower unit energy cost if the energy credit from the waste treatment step produces an attractive return on that portion of the investment.

As mentioned above, ORF is also looking at wet carbonization of hydro-peat. The overall thermal efficiency of this process is expected to be higher than the hot water and steam route. This factor, along with other process refinements, may produce significant reductions in unit energy cost.

A market assessment for the wet carbonized PDF should be done in Canada. This type of fuel can be used in properly retrofitted oil-burning utilities and industrial facilities, without the need for flue gas desulfurization equipment; other markets may also exist in the area of residential, institutional and commercial space heating. In areas where significant market potential exists for PDF, site-specific economic analyses should be made.

The market analysis mentioned above would provide information for location of the first Wet Carbonization demonstration project in Canada.

Further work in the field of biogasification of peat is definitely needed before the full potential of the conversion technology can be fully assessed. Priority should be given to

research in the areas of pretreatment and chemical recovery to improve methane conversion, minimizing environmental impact and lower production costs, and high-rate anaerobic technology to improve both rates and degree of conversion. Optimization in these areas will certainly reflect significant reductions in unit SNG energy costs.

LIST OF FIGURES

Figure 1 - Dynatech Biogasification Process p. 14

Figure 2 - IGT Biothermgas Process Schematic p. 17

Figure 3 - Wetox Process Schematic p. 40

Figure 4 - Simplified Process Flow Diagram for Peat Wet Carbonization p. 41

LIST OF TABLES

Table 4.1 - Information Sources Used in Developing Cost Estimates p. 25

Table 4.2 - Dynatech Biogasification Process Base Case Design Process Assumptions p. 27

Table 4.3 - Dynatech Biogasification Process Mass Balance p. 29

Table 4.4 - Dynatech Biogasification Process Energy Balance p. 30

Table 4.5 - Dynatech Biogasification Base Case Capital Costs p. 31

Table 4.6 - Dynatech Biogasification Base Case Annual Costs p. 32

Table 4.7 - Biothermgas Process System Details p. 34

Table 4.8 - Characteristics of Bermuda Grass p. 35

Table 4.9 - IGT Biothermgas Process Base Case Capital Costs p. 36

Table 4.10 - IGT Biothermgas Process Base Case Annual Costs p. 37

Table 4.11 - Comparison of Project Unit Energy Costs p. 39

Table 4.12 - Densified Fuel Peat Base Case Capital Costs p. 42

Table 4.13 - Densified Fuel Peat Base Case Annual Costs p. 42

Table 4.14 - Wet Carbonization Process Base Case Capital Costs p. 44

Table 4.15 - Wet Carbonization Process Base Case Annual Costs p. 44

Table 4.16 - Wetox Process Base Case Capital Costs p. 45

Table 4.17 - Wetox Process Base Case Annual Costs p. 45

Table 4.18 - Effects of Cost Adjustments Upon Unit Costs p. 49

NOMENCLATURE

Btu	- British thermal unit
°C	- temperature in degrees Celsius
CRF	- Capital Recovery Factor
d	- day
GJ	- gigajoule = joule x 10^9
hp	- horsepower
IGT	- Institute of Gas Technology
kg	- kilogram
kPa	- kilopascals
kWh	- kilowatthour
MC	- Moisture Content
MJ	- megajoule = joule x 10^6
m^3	- cubic metres
min.	- minute
NIC	- not included
PDF	- Peat Derived Fuel
R/D	- Research and Development
SNG	- Substitute Natural Gas
std.	- standard
TJ	- terrajoule = joule x 10^{12}
US DOE	- United States Department of Energy
VS	- Volatile Solids
W	- Watt
%	- percent

APPENDIX A

ANNOTATED BIBLIOGRAPHY

1. LeDuy, A., "Microbial Bioconversion of Peat--A Perspective" presented at the Symposium on "Peat as an Energy Alternative" Arlington, Virginia, December 1980, Institute of Gas Technology, Chicago, Illinois.

The microbial bioconversion processes might transform peat into various useful forms of bioenergy such as biochemical (foods and feeds), chemical (solid, liquid and gaseous fuels), electrical (biofuel cells), luminescent (light), and thermal (heat) forms. This paper presents a general discussion of the possibilities of obtaining these useful forms of bioenergy by the microbial bioconversion of peat biomass.

2. Merlin, E., Norrbin, S., and Oden, S., "Researches on the Methane Fermentation of Peat," Ingeniorsvetenskapsakademiens, Hanlingar No. 53, (Stockholm), 1926.

Digestion runs were carried out with various samples of Sphagnum and Magnocaricetum peat at mesophilic temperatures of 25°C to 30°C in aqueous media containing external nutrients (ammonium chloride, potassium phosphate) and carbon sources (calcium acetate, waste materials) to stimulate peat digestion. The total gas yields from these experiments were low [less than 0.06 m^3/kg VS (volatile solids) added], and these yields were obtained when the amount of organic matter contained in the inoculum (Imhoff sludge and horse manure) was considerably greater than that of added peat. Depending on the type of peat, the digester gases contained 5% to 14% CO_2, 0.1% to 0.2% CO, 0.7% to 3.2% O_2, 13% to 30% H_2, 58% to 78% CH_4, and 0 to 17% N_2. It was difficult to maintain vigorous peat fermentation on a continuing basis because a "degeneracy of bacteria" occurred with time.

(Reference and details from Reference 4.)

3. Kaleja, E., "Fermentation of Natural Substrates Under Thermophilic Conditions" in Bekeris, M., (Editor), Mikrobynyi Sin. Biol. Vazhnykh Veshchestu, 123-129, Riga, U.SS.R., 1968; Chem. Abstr. 71 (1969) No: 122351b.

Experiments were conducted with mixed cultures at 56°C in a semicontinuous digester operated at a detention time of 10 to 20 days. A variety of cellulose-and-carbohydrate-decomposing, sulfate-reducing, ammonifying, deritrifying and methane-forming organisms were isolated from the peat-digesting cultures. (Reference and details from Reference 4.)

4. Ghosh, S., and Klass, D.L., "Methane Production from Peat by Anaerobic Digestion," presented at Symposium on Energy From Biomass and Wastes, Washington, D.C., August 1978, Institute of Gas Technology, Chicago, Illinois.

The high moisture content of peat, the occurrence of peat in large concentrations of fermentable organics of plant origin, the use of hydraulic peat mining techniques, and the possibility of recycling digested peat residue to the peat bogs are factors that support the position that biological gasification methods can be effectively utilized. Chemical characterization work indicated that peat is rich in organic matter, has all the essential elements needed for biological gasification, and should, in theory, be digestible. However, the chemical analyses also point to three possible impediments to vigorous digestion of peat: (1) The presence of peat of large concentrations of cellulose, hemicellulose, lignin, and other complex substances of low biodegradabilities; (2) The nonavailability of such essential elements as nitrogen, phosphorus, etc., that are mostly organically bound; and (3) The toxicities arising because of nitrates and other inhibitors.

The work reported here consisted of exploratory digestion runs designed to study the effects of such factors as digestion mode, inoculum source, temperature, loading, detention time, feed particle size, and chemical pretreatment on peat digester gas yield, production rate, and gas quality. Work with Minnesota Reed Sedge Peat showed that it could be digested in both batch and continuous modes with or without external nutrient additions.

A thermophilic temperature of 55°C effected higher gas yields than other mesophilic or thermophilic test temperatures. A thermophilic (55°C) methane yield of 0.14 std m^3/kg VS (volatile solids) added was obtained with raw as-received peat during batch digestion for about 86 days, compared with a methane yield of 0.11 std m^3/kg VS added observed during semicontinuous thermophilic (55°C) digestion at a 60-day detention time and 0.80 kg VS/m^3-day loading. Subsequent batch digestion showed that particle size reduction and acid or alkali treatment could cause a three-fold increase in methane production over that obtained with raw untreated peat. This suggests that a methane yield of up to 0.31 std m^3/kg (5 SCF/lb) VS added--which is about 60% of the maximum theoretical yield--may be obtained by optimizing the digestion and feed pretreatment conditions.

5. Ghosh, S., and Klass, D.L., "Biomethanation of Minnesota Reed Sedge Peat," Resource Recovery and Conservation, Vol. 4, 115-139, 1979.

This paper is essentially the same as Item 4 except for the title.

6. Ghosh, S., "Biogasification of Pretreated Reed Sedge Peat" presented at 6th International Peat Congress, Duluth, Minnesota, August 1980.

Chemical characteristics of Minnesota Reed Sedge Peat indicated that for anaerobic digestion, this substrate could be deficient in phosphorus, sodium, potassium, and magnesium. Hydrolysis of this feed with 8% HCl solution at 132°C and 193 kPa gage substantially increased volatile acid and gas production over that observed with untreated feed. Thermophilic (55°C) digestion afforded higher gas and methane yields than the mesophilic temperature. The highest methane yield of about 0.12 std m^3/kg VS added was observed at a retention time of 24 days at the thermophilic temperature. This yield corresponds to an energy recovery efficiency of 20%, and is three times that of digestion

of untreated peat at a comparable retention time of 30 days. Addition of large quantities of sewage sludge (about 50 wt % of the feed on a VS basis) greatly improved methane yield up to 0.29 std m^3/kg VS added. A lower sludge dosage of 15 wt % did not enhance gas production from peat. Addition of mixed inorganic nutrient substantially improved methane production from peat. Surprisingly, a pH of about 6.4 was found to be optimum for mesophilic and thermophilic digestion of peat. Dilute digested slurries could be dewatered by vacuum filtration and mechanical pressing to afford 34 wt % solids-content cakes.

The study concluded that additional research should be undertaken to optimize the peat hydrolysis process, digester loading and retention time, bioreactor design and digestion mode, nutrient supplementation, and digested peat dewatering.

7. Ghosh, S., "Biomethanation of Peat" presented at International Peat Symposium, Bemidji State University, Bemidji, Minnesota, October 1981.

The United States has vast reserves of peat that could be tapped for synthetic fuel production to augment its indigenous energy supply. The feasibility of methane production by anaerobic digestion is reviewed in this paper. Results of digestion studies conducted to study the effects of digestion mode, inoculum source, fermentation temperature, digester loading, hydraulic retention time, external nutrients, peat particle size, and acid and alkaline pretreatment of feed are discussed. Enhanced methane production was obtained at an acidic pH, with external nutrients, and when the peat was pretreated with alkali or acid.

8. Chynoweth, D.P., Srivastava, V.J., Henry, M.P., and Tarman, P.B., "Biothermal Gasification of Biomass" presented at Symposium on Energy From Biomass and Wastes IV, Lake Buena Vista, Florida, January 1980 (Institute of Gas Technology, Chicago, Illinois).

The BIOTHERMGAS Process is described for conversion of biomass, organic residues, and peat to substitute natural gas (SNG). This new process, under development at IGT, combines biological and thermal processes for total conversion of a broad variety of organic feeds (regardless of water or nutrient content). The process employs thermal gasification for conversion of refractory digester residues. Ammonia and other inorganic nutrients are recycled from the thermal process effluent to the bioconversion unit. Biomethanation and catalytic methanation are presented as alternative processes for methanation of thermal conversion product gases. Waste heat from the thermal component is used to supply the digester heat requirements of the bioconversion component. The results of a preliminary systems analysis of three possible applications of this process are presented: 1) 10 000 ton/day Bermuda Grass plant with catalytic methanation; 2) 10 000 ton/day Bermuda Grass plant with biomethanation; and 3) 1 000 ton/day municipal solid waste (MSW) sewage sludge plant with biomethanation. The results indicate that for these examples, performance is superior to that expected for biological or thermal processes used separately. The results of laboratory studies presented suggest that effective conversion of thermal product gases can be accomplished by biomethanation.

9. Srivastava, V.J., Novil, M., Tarman, P.B., and Chynoweth, D.P., "Hybrid Biothermal Conversion of Biomass to Methane" in "Biogas and Alcohol Fuels Production," Vol. II, The J.G. Press, Emmaus, PA 18049, 1981.

A preliminary evaluation of IGT's BIOTHERMGAS Process has shown that combining biochemical and thermochemical gasification results in an economic process with a higher conversion efficiency and a greater choice of feedstocks that can be processed than either biological or thermochemcial processes used separately. The biogasification component can receive high moisture feeds, can convert major portions of feed at low temperature and pressure, and can be used for methanation of synthesis gas. The

thermochemical gasifier converts refractory organic residues from the anaerobic digesters and provides gases that can be used for heating, mixing, and stimulating methanogenesis in the biological component.

Research planned for further demonstration of the technical and economic feasibility of the process will include further evaluation of the process at the laboratory scale, a more detailed systems and economic study, and process design and scale-up.

10. Chynoweth, D.P., Srivastava, V.J., Jerger, D.E., and Tarman, P.B., "Biothermal Conversion of Biomass to Methane and Alcohols" presented at 9th Energy Technology Conference, Washington, D.C., February 1982.

Conversion of biomass and organic residues to synthetic fuels can be accomplished by biological or thermal conversion processes. Because of large variations in the physical and chemical characteristics of these feedstocks, no single process is suitable for conversion of all types of biomass. Many feedstocks are either insufficiently biodegradable or lack the proper nutrient balance for bioconversion; others contain too much water for thermal conversion. Current studies at IGT are evaluating combinations of biological and thermal processes that can be used to convert all types of biomass to methane or alcohol fuels.

One process under development for the production of methane employs anaerobic digestion followed by thermal gasification. High- or low-moisture content feeds are subjected to anaerobic digestion, and the refractory nonbiodegradable residues are dewatered and thermally gasified. Nutrients produced in the thermal gasification step are recycled to enhance the bioconversion step. The bioconversion step is also used to clean and upgrade the thermally-produced synthesis gas by biomethanation. In addition, the synthesis gas provides a means for heating, mixing, and stimulation of methanogenesis in the bioconversion

step. The process is cost-competitive and has a thermal efficiency superior to other processes.

Another process under study combines fermentation with thermal conversion for production of separate streams of ethanol and methanol. This process employs fermentation for production of ethanol, and thermal conversion of fermentation residues for production of synthesis gas and methanol. Thermal process heat and a portion of the synthesis gas are used to supply the energy required for feed pretreatment, fermentation, and alcohol purification. The output of alcohol (ethanol plus methanol) is approximately double that obtained by conventional fermentation processes.

11. Buivid, M.G., Wise, D.L., McCarty, P.L., and Owen, W.F., "Feasibility of a Peat Biogasification Process," Resource Recovery and Conservation, Vol. 5, 117-138, 1980.

A feasibility study was carried out for the Minnesota Gas Company to determine if biogasification may be a technical and economical process for the conversion of peat into pipeline quality methane (SNG). U.S. peat resources, in terms of energy content, are greater than the maximum recoverable energy from uranium, shale oil, or the combined reserves of petroleum and natural gas. Experiments and costing of SNG by the biogasification of peat were based on a two-stage process. In the first processing stage (assumed to follow wet harvesting of peat), an alkaline oxidation pretreatment of peat was employed to produce soluble, low molecular weight acids, wood sugars, and other soluble organic fragments. Unreacted peat solids were separated (to be processed as boiler fuel), while the recovered liquid containing the soluble organic material was anaerobically fermented to methane and carbon dioxide in the second stage of the process. In this study, up to 26 percent of the energy value in peat was converted to methane in the two-stage process. However, up to

over 50 percent of the material from the first stage was fermented to methane in the second stage. More work is needed to optimize the first stage. Preliminary cost estimates show that for a 79.2 x 10^3 GJ/day (75.0 billion BTU/day) plant, the total capital requirement was approximately $323 million (using April 1978 costs). The annual operating cost was approximately $44 million. For a plant operating at a 90% stream factor, with peat delivered to the plant site as a 3% solids slurry at a cost of $0.0033/kg ($3/ton) dry peat, the average cost for SNG was estimated to be $3.16/GJ ($3.34/million BTU). The gas cost was calculated using a computer model of the process which incorporated the utility financing method used by the American Gas Association. A significant advantage of the biogasification processing route appears to be that technical difficulties of dewatering, necessary for peat utilization in conventional gasification or direct combustion, are eliminated.

12. Peat Biogasification Development Program. Quarterly Progress Report No. 1, Oct. 1-Dec. 31, 1979 by Dynatech R/D (US DOE/ET/14696-T1).

Batch experiments have been performed to determine the effects of different alkalis, temperatures, and oxygen partial pressures on the solubility of peat organic material. Multi-stage pretreatment was investigated by pretreating the effluent from previous NaOH pretreatment cooks. Bacteria from three inoculation sources are being grown anaerobically on a growth medium containing a standard nutrient medium and one of 12 aromatic compounds. The concentration of aromatic compound is increased gradually to acclimate the bacteria to compounds which may result from peat pretreatment. These bacteria are being prepared for future digestion of pretreated peat. Laboratory procedures to determine pretreated solids energy content and pretreated solids dewatering characteristics are being developed. The environmental effects of liquid effluent disposal into the peat

bog is being evaluated through a review of relevant literature. A preliminary design for a full-scale peat biogasification plant has been developed. The plant is designed to produce 75 x 10^6 SCFD of pipeline quality methane. Major segments of the plant are concerned with the transport, handling, pretreating, and fermenting of the aqueous peat slurry, and the purification of the resulting methane gas. The information necessary for continuous PDU scale operation is being evaluated as part of Task 4. A detailed proposal for specific design plans and experiments has not yet begun, however.

13. Peat Biogasification Development Program. Quarterly Progress Report No. 2, Jan. 1-March 31, 1980 by Dynatech R/D (US DOE/ET/14696-T2).

Batch experiments have been performed to determine the effects of different alkalis, temperatures, retention times, solids loading, and oxygen partial pressures on the solubility of peat organic material. Oxidation experiments have been performed simultaneously with and separately from solubilization. In both cases, kinetic information has been developed based on oxygen consumption. Kinetics based on fermentable product formation are dependent on satisfactory identification methods. Development of analytical procedures for product identification have included: gel permeation chromatography (GPC), solvent extraction, aldehyde precipitation, and thin-layer chromatography (TLC). Microorganisms from three inoculation sources are being grown anaerobically using a growth medium containing a standard nutrient and a specific substrate, one of twelve aromatic compounds. The concentration of aromatic compound was increased gradually in order that bacteria acclimate for future use as inocula with pretreated peat liquors. Acids and methane production are being monitored for pretreated peat liquor fermentations using an acclimated microorganism inocula. Apparent viscosity and apparent heat transfer coefficient data are being

obtained at three peat slurry solids concentrations (3-5, 10, 15% total solids). A 75% heat recovery would give a positive energy balance around the pretreatment reactor. Development has continued in regards to full-scale peat biogasification design (75×10^6 SCFD, pipeline quality methane). The information necessary for continuous PDU scale operation is being evaluated in terms of what processing information may be obtained from various scale units, batch and continuous.

14. Peat Biogasification Development Program. Quarterly Progress Report No. 3, April 1-June 30, 1980 by Dynatech R/D (US DOE/ET/14696-T3).

Procedures for high-pressure liquid chromatography (HPLC) are under development that will identify and quantify fermentable material contained in pretreated peat liquors. Several of the model compounds hypothesized to be a product of peat pretreatment have been identified with HPLC and confirmed with thin-layer chromatography (TLC). However, there are numerous unknown peaks of other products for which elution times and extinction coefficients must be determined in order to make HPLC a quantitative analytical tool for kinetic data.

15. Peat Biogasification Development Program by Dynatech R/D Company, U.S. Department of Energy, DOE/ET/14696-T6, April 21, 1981.

This is the final report of the two-year study by Dynatech R/D. The phases of this peat biogasification program included an experimental study to define the solubilization, oxidation and digestion steps sufficiently. Based on the results of the experimental study, a preliminary conceptual design and a preliminary economic analysis of the process [8 350 tpd (dry basis) plant] was developed. The results of the sensitivity analysis showed that apart from feedstock cost, the digester detention time and alkali chemical costs are the important sensitivity variables which affect the unit gas cost.

The study concluded that biogasification of peat to pipeline-quality methane is technically feasible and that further research and development work is required.

16. Ruoff, C.F., Ashare, E., Sanderson, J.E., and Wise, D.L., "Continued Development of a Peat Biogasification Process," presented at the Symposium on "Peat as an Energy Alternative," Arlington, Virginia, December 1980 (Institute of Gas Technology, Chicago, Illinois).

Based on the results of an earlier feasibility study, continued development was carried out on a peat biogasification process. The process is based on total wet processing of peat including: a) hydraulic mining and slurry pumping of the wet-harvested peat to the processing plant; b) aqueous alkali oxidation of the peat slurry to break the complex peat structure into lower molecular weight fermentable fragments; and c) anaerobic methane fermentation of the "cooked" peat liquor. The present work reported has been oriented towards obtaining a definitive process model on which full-scale plant economics may be based. The process model consists of three system components, namely: a) peat solubilization; b) peat oxidation; and c) peat fermentation. While both solubilization and oxidation may be carried out in the same reaction vessel, it has been determined that these are two discrete processing steps. It has been further determined that peat solubilization follows first-order reaction kinetics with respect to peat and alkali concentrations with a rate constant of $k = 258.1$ (ℓ/gmole hr) at 100°C and an activation energy of $E_a = 5.7$ kcal/gmole. The oxidation of solubilized peat has been found to follow second-order reaction kinetics for oxygen consumption with an activation energy for this oxidation of 22.6 kcal/gmole. It has been determined that methane fermentation of the "cooked" peat or peat liquor follows first-order reaction kinetics; moreover, selected water soluble aromatic compounds such as benzoic acid and syringic acid--identified by HPLC analysis as being in the peat liquor--were independently

fermented to fuel gas with first-order reaction kinetics of k = 0.184 day^{-1} and k = 0.130 day^{-1}, respectively. Overall, the process development to date indicates that peat biogasification is uniquely suited for recovery of the energy value in peat in the form of pipeline quality gas. Moreover, projections based on experimental work to date indicate decidedly lower capital costs with peat biogasification than with conventional coal gasification technology applied to peat.

17. Buivid, M.G., Rader, A.H., Wise, D.L., and Kopstein, M.J., "Status of Peat Biogasification Development," Proc. Intersoc. Energy Convers. Eng. Conf. 15th, Energy to the 21st. Century, V2, Seattle, Washington, August 18-22, 1980. Published by AIAA, New York, NY, 1980.

The status of a four-phase development program to confirm that biogasification is a technically feasible and economical process for the conversion of peat into pipeline quality methane is presented. The biogasification of peat is based on a two-stage process.

18. Ruoff, C.F., Ashare, E., and Wise, D.L., "Continued Technical Development of a Peat Biogasification Process," Dynatech R/D Company, Cambridge, Massachusetts, 1980.

A bench-scale experimental development program and the development of an economic process model, were conducted for the conversion of peat to substitute natural gas (SNG). This work is a continuation of an earlier feasibility study. The process consists of three steps: a) hot (150°C) aqueous alkali [soda ash (Na_2CO_3)] solubilization of peat. Solubilization results in the complex ligneous structure of peat being broken down into single-ring aromatics with one or more 3 to 5 carbon side chains; b) oxidation of the solubilized peat--resulting in oxidation of the side chains on the peat-derived aromatics, the exothermic reaction also providing the process heat; and c) anaerobic fermentation of the solubilized/oxidized peat liquor to fuel gas.

While both solubilization and oxidation steps may be carried out in the same peat pretreatment reaction vessel, it was determined that these are two discrete processing steps. It was found that peat solubilization follows first-order reaction kinetics with respect to peat and hydroxyl ion concentrations with a rate constant, k_s, equal to 2.30×10^6 exp [-3300/T(°K)] (/hr-gmole). The oxidation of solubilized peat was found to follow first-order reaction kinetics with respect to solubilized peat and oxygen with a rate constant, k_o, equal to 7.5×10^{14} exp [-14650/T(°K)] (/gmole hr). It was further experimentally determined that methane fermentation of the pretreated peat followed first-order kinetics; the rate constant was 0.015 $days^{-1}$ under mesophilic (37°C) and continuous fermentation conditions. This constant is believed to be low, primarily due to sodium inhibition caused by the presence of the soda ash. Methane fermentation of pure model compounds, assayed in the peat liquor, were much higher; for example 0.13 day^{-1} for benzoic acid and 0.18 day^{-1} for syringaldehyde. The fuel gas processing cost was calculated using the utility financing method approved by the American Gas Association and the kinetics and yields determined experimentally. A very conservative "base cost" average cost for pipeline quality methane was determined to be $5.93/million Btu for a 70 billion Btu/day plant processing over 8 000 tons/day (dry) of peat. A sensitivity analysis revealed that the alkali requirements and digester volume were most critical to the methane cost and that by further process development, the average gas cost may be expected to be reduced to 3 to 4 $/million Btu.

19. Martinell, R., "The Vyrmethane Method," presented at the Symposium on Peat Energy, Stockholm, Sweden, April 25, 1979. Ingenjoersvetenskapsakademien, pp. 50-56, June 1979.

A method for in situ gasification of peat is described. The process is under development. Some ideas about the economy and production volumes are given.

20. Martinell, R., "Vyrmethane, Bacteriological In Situ Gasification of Peat to Methane," document distributed at the Bio-Energy 1980 World Congress and Exposition, Atlanta, Georgia, April 1980.

The pilot-scale experiments for in situ production of methane from peat bogs were conducted in Sweden. In this process, the methane naturally produced in peat bogs was dissolved in groundwater. This methane-rich water was pumped to a degassing station above ground, where the methane was separated. The water was then recycled underground for reuse. The concentration of methane in water of 20 mg/l was reported under a circulation water flow rate of 100 l/s. It was estimated that about 35% of the methane produced was consumed for maintaining the process operation. This process is very interesting in its very low operating cost, inexpensive transportation and handling of raw materials, and relatively low capital cost.
(Reference and details taken from Reference 1.)

21. "Evaluation of the Potential of Peat in Ontario" prepared by Monenco Ontario Limited, Ontario Ministry of Natural Resources, Mineral Resources Branch, Occasional Paper No. 7, 1981.

This report was prepared under contract by consultants (Monenco Ontario Limited) for the Mineral Resources Group of Ontario Ministry of the Natural Resources. This report provides the first overall view of the possible uses and the opportunities for the development of peat in Ontario. It examines all peat mining techniques, peat processing technologies including biogasification, potential applications, environmental impacts and regulatory guidelines required. It makes recommendations for future course of action in the area of peat development and utilization in Ontario.

22. Wise, D.L., Cooney, C.L., and Augestein, D.C., "Biomethanation: Anaerobic Fermentation of CO_2, H_2 and CO to Methane," Biotechnology and Bioengineering, Vol. 20, pp. 1153-1172, 1978.

Studies to examine the microbial fermentation of coal gasification products (CO_2, H_2 and CO) to methane were done with a mixed culture of anaerobic bacteria selected from an anerobic sewage digestor. The specific rate of methane production at 37°C reached 25 mmol/g cell hr. The stoichiometry for methane production was 4 mmol H_2/mol CO_2. Cell recycle was used to increase the cell concentration from 2.5 to 8.3 g/liter: the volumetric rate of methane production was from 1.3 to 4 liter/liter hr. The biogasification was also examined at elevated pressure (450 psi) and temperature to facilitate interfacing with a coal gasifier. At 60°C, the specific rate of methane production reached 50 mmol/g cell hr. Carbon monoxide utilization by the mixed culture of anaerobes and by a Rhodopseudomonas species was examined. Both cultures are able to carry out the shift conversion of CO and water to CO_2 and hydrogen.